Utilizing Sensed Incipient Slip Signals for Grasp Force Control

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Abstract

We present a scheme by which a manipulator can identify when it is about to lose hold of a grasped object so that it can take preventive measures to maintain the grasp before slipping occurs. By detecting localized slips which precede gross slip between the gripping surface and a grasped object, a controller can reliably modify the grasp force and prevent the object from slipping. The motivation behind our sensor design comes from current physiological research which reveals the importance of a textured gripping surface in detecting these localized, or incipient, slips and provides us with insight into human grasping and manipulation strategies. By using our sensor as an active gripping surface on a simple manipulator and modeling our control strategy after humans, we are able to dynamically control the amount of force used to grasp objects, while preventing them from slipping. Our results show that the sensor is not greatly affected by variations in the material properties of the grasped object and indicate that the force control strategy is adequately immune to mechanical vibrations in the manipulator.

1   Introduction

When people grasp and manipulate objects, their grasp force is continually adjusted to maintain a margin above the minimum required to prevent slipping. The human hand responds to signals from dynamic, or "fast-acting" receptors in the skin that respond to small, localized slips that are the precursors to gross sliding [Johansson and Westling 1990; Srinivasan et. al. 1990]. The grasp force response is unconscious and has a latency of approximately 80msec. The margin of safety associated with the ratio of normal/tangential force at each fingertip contact varies from approximately 15% to 100%, depending on the material and texture of the object being handled. The sensing of small slips is combined with prior expectations in performing grasp control. If no slips are detected, the hand gradually relaxes so that the grasp force undergoes an approximately exponential decay.

The result of this dynamic grasp force control is to provide humans with several advantages over robots, which typically must grasp with a predetermined force. The most obvious advantage of grasp force control based on incipient slip information is that it allows people to minimize grasp forces, saving energy and reducing damage to delicate objects. However, as the contact forces at the fingertips automatically adapt to variations in task loading or surface conditions (e.g., the presence of dirt or moisture), other advantages accrue which are probably more important for everyday manipulation. In particular, closed-loop control of the normal/tangential force ratio at the fingertips is particularly useful for manipulation with sliding [Kao and Cutkosky 1992]. Also, by keeping the contact forces small, the sensitivity and available dynamic range of the tactile sensors is enhanced. This is partly because saturation of the sensors is avoided and partly because the compliance of a fingertip decreases with increasing contact force. The deformation of a fingertip varies as $\delta x = c \delta f$, where c is compliance (inverse of stiffness). Therefore, as the fingertips are pressed harder against a surface, the relative change in skin and tissue deformation for a given change in force decreases, and the fingertips become less sensitive. Finally, keeping the contact force slightly above the threshold for slipping ensures that micro-slips will often occur. This is useful because a change in the incidence of micro-slips can also be an indication of changing contact conditions and/or task loading.

Although humans evidently benefit from being able to continually adjust grasp forces using incipient slip information, comparatively little has been done to provide such capabilities for robots. Early slip sensors for robotic hands and grippers employed small styli, rollers and balls that worked much like the ball in a "mouse" used for graphical input on computers [Ueda et. al. 1972; Tomovic and Stojiljkovic 1974; Masuda et. al. 1976]. More recently, Dario and Rossi [1985] have described a piezoelectric device which senses micro-vibrations resulting from relative motion between a slipping object and the fingertip. With this device they could detect object displacements as small as a few hundred micrometers occurring within a few milliseconds. However, all of these devices suffer from being activated by motion of the object. In other words, for such devices to send a signal, gross sliding must already have initiated, and there is consequently little time to increase the grasp force before significant object movement takes place. The problem is most evident when the static and dynamic coefficients of friction are dissimilar; once the object starts to slip, it is very difficult to recover control of

the grasp.[1] In addition, there are practical concerns with such devices about the durability of styli or rolling elements that must come into contact with possibly dirty or abrasive objects.

Other efforts have focused on the changes in signals from tactile array sensors to indicate the presence and direction of sliding [Rebman and Kallhammer 1986]. This approach avoids the use of delicate styli or rollers. However, the sensitivity of this approach is limited by the spatial resolution of the array and by the frequency with which an array of elements can be scanned and processed.

A different approach has involved the use of acoustic emissions (AE) to directly detect localized slips at the gripper/object interface. Dornfeld and Handy [1987] describe an AE sensor that can detect the onset of slipping between a metal gripper and workpiece. Cuttino, Huey and Taylor [1988] take a combined analytical and experimental approach to the problem of sensing incipient slip with rubber fingertips. Using a finite element model of the object/finger interface, they are able to show, qualitatively, that a period of local slip precedes the onset of gross sliding. In an effort to detect this phenomenon experimentally, a test fixture was constructed to detect AE signals from the contact. Although the detection of incipient slip was generally unsuccessful, it was possible to verify the existence of a transition phase between complete object contact and gross slip.

Dynamic tactile sensors can also detect the onset of slipping. Howe and Cutkosky [1989; 1992] describe two kinds of dynamic sensors for use with soft robotic fingertips. For soft fingertips, the contact pressure is not uniform and lightly loaded parts of the contact typically experience small slips before gross sliding occurs. The micro-slips result in vibrations which the sensors can detect. In subsequent work, Howe [1992] has found that skin acceleration sensors can be used to detect the onset of sliding when objects are handled by a force-reflecting master-slave manipulator, thereby permitting a human operator to determine not only how hard the slave gripper is grasping but also when the grasp force approaches the minimum required to prevent slipping. Finally, in developing a perceptual scheme for legged locomotion, Sinha and Bajcsy [1992] use a foot mounted accelerometer to detect the onset of gross slip and prompt the controller to increase the normal contact force in order to increase traction.

In summary, the present status of robotic slip sensing is that a few promising sensors have been developed, and preliminary results under carefully controlled conditions have been reported in the literature. However, before such sensors can be employed in general-purpose manipulation, a number of questions must be addressed concerning the repeatability and robustness of the sensor signals, the sensitivity of the signals to variations in materials and textures and the vulnerability of the sensors to electromagnetic and mechanical noise. The work described in this paper is an attempt to address some of these issues in the context of closing a grasp force control loop based on the sensing of incipient slips.

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[1]This is one reason why a wet bar of soap is so difficult to handle; once the bar starts to slide, hydrodynamic lubrication produces a friction coefficient that is much lower than the static coefficient, with the result that one cannot regain control.
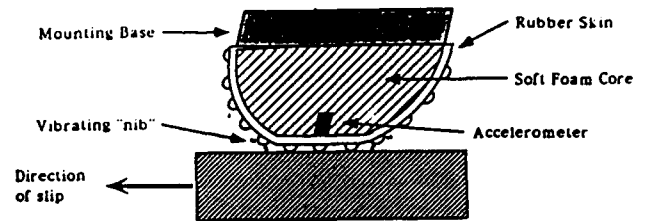

Figure 1: Sensor design

2 Sensor design

The sensor used for the experiments described in this paper is a modification of the skin acceleration sensor described by Howe and Cutkosky [1989]. The sensor consists of a thin outer skin of textured rubber over a hemicylindrical core of foam rubber (Figure 1). The foam helps the fingertip to conform to features on the grasped object, improving the stability of the grasp. The foam also partially isolates the skin from structural vibrations in the manipulator. The rubber skin is typically made from either a latex or silicone rubber, and is secured to the outer surface of the foam. Rubber "nibs" (projections) on the skin form local contact regions that can start to slip and vibrate independently of each other. Like the ridges on human fingerprints, the nibs also provide more reliable friction properties than smooth skin when grasping dirty or wet objects.

The slip sensor performs in a similar manner to the human FAII tactile receptors [Johansson and Westling 1984]. When the sensor first makes contact with an object, the outer skin compresses to conform to the surface of the object. As the load force (tangential force) increases to the point where the critical slip ratio is approached, the nibs at the periphery of the contact area spring free before the rest of the object slips with respect to the fingertip (Figure 1). By detecting the resulting vibrations which are propagated throughout the skin, a manipulator has sufficient time to increase the grasp force and avoid, or minimize, gross slip of the grasped object. It is conjectured that the nibs at the periphery will be solely responsible for the detected vibrations (prior to gross slip) because localized slip away from the edges will be heavily damped by contact friction and adhesion with the object surface. This assumption is consistent with the studies from the literature on sliding rubber [Schallamach 1957].

The active element in the slip sensor is a conventional quartz crystal miniature accelerometer which is bonded to the inner surface of the outer layer of skin. The sensor has a dynamic range between 1 Hz and 25 kHz, making it well suited for sensing incipient slip. For best results, care should be taken to prevent the foam substrate from contacting the accelerometer case so that it responds only to
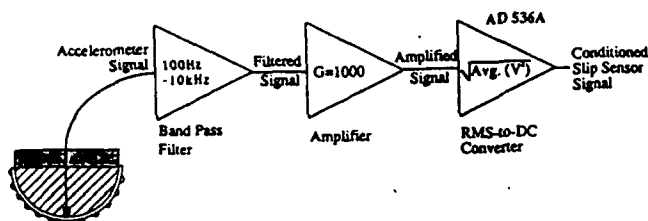
Figure 2: Instrumentation

TOP VIEW

FRONT VIEW

Figure 3: Experimental setup

vibrations of the outer skin. As the accelerometer weighs less than 0.5 grams, it is unobtrusive and does not affect the performance of the manipulator.

The incipient slip signals are usually brief (less than 20 msec). It is therefore useful to feed the accelerometer signal through an RMS-DC converter to ensure detection when sampling at moderate servo rates of approximately 320Hz. The instrumentation is shown in Figure 2. The accelerometer signal is first amplified and then passed through a band-pass filter and RMS-DC converter. The output of the RMS-DC converter is a measure of the energy of the incipient slip signal. The rise and settling times of the converter are adjusted with an external capacitor.

3 Experimental Setup and Procedure

As shown in Figure 3, the setup used for experimenting with grasp force control was essentially one half of a symmetric two-fingered grasp. A slip sensor was mounted at the end of a manipulator finger and made to bear against an object that could slide freely on a low friction (0.05 Newtons to initiate and sustain motion) Teflon track. A 70 gram mass was attached to the object, providing a tangential force that caused the object to slide whenever the normal force exerted by the fingertip dropped below a minimum threshold, determined by the coefficient of friction.

The finger is part of a direct-drive manipulator that has been described previously in [Howe et al., 1990]. It is a two degree of freedom, direct-drive 5 bar linkage and is well suited to experiments in force control due to the absence of backlash, cable elasticity and similar drive train effects. A three-axis force/torque sensor is mounted just behind the fingertip to measure the normal and tangential force at the fingertip to an accuracy of approximately $\pm0.02N$. The fingertip is controlled using a hybrid force/position controller running at 320Hz, that maintains control of the force in the normal direction and displacement in the tangential direction.

As a means of determining the displacement and acceleration of the grasped object, we have instrumented the work piece with an accele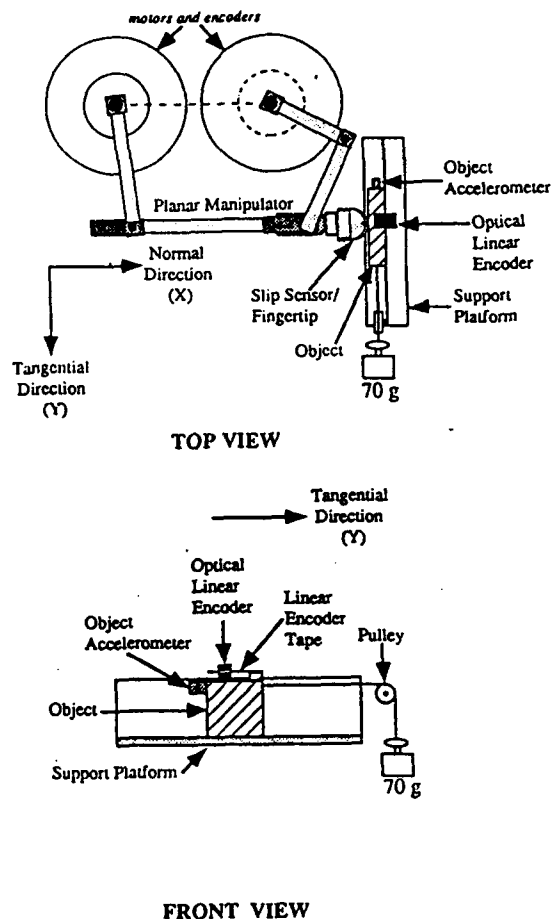rometer and a non-contact linear encoder with a resolution of 0.042mm/count. The output of the accelerometer is sent through a low pass filter, to avoid aliasing, and amplified.

The experimental procedure begins as the normal force at the fingertip is gradually increased to 1.17 Newtons (120 grams), as measured by the fingertip force sensor. The commanded normal force is then gradually decreased in an exponential decay curve:

$$\text{Grasp Force}(t) = F_o e^{-at}$$

where $F_o = 1.45N$ and $a = 0.192$.

This decay rate is slightly faster than the decay curves observed in human subjects [Westling and Johansson 84]. The decay continues until an incipient slip signal is registered from the slip sensor. When this occurs, the normal force is immediately increased in an effort to avoid gross slip. This is similar to the way in which humans, noncognizantly, increase the grasp force in response to local slips. With the work piece firmly grasped once again, the

controller resumes its decaying normal force until local-
ized slips are again detected. This pattern continues for
a duration of ten seconds, at which time the experiment
ends.

The experiments were performed for a variety of object
surface materials, including #410 grit sandpaper, paper,
teflon and a fine-weave cloth. The initial commanded force
and the decay rate were held constant for all trials.

4   Results and Discussion

Four plots from a representative grasp experiment using
fine sandpaper as the surface material are illustrated in
Figure 4. The plot of the normal grasp force clearly shows
the different phases of the experiment. For the first 2 sec-
onds, the manipulator finger moves into place and ramps
the grasp force up to an initial value of 1.17 N (120 grams),
high enough to ensure firm contact with the object and to
prevent any localized slips. During the first two seconds,
signals from the slip sensor are ignored to give the fingertip
time to settle and thus aren't displayed in Figure 4. The
force then begins to decay. Once the fingertip has been
allowed to settle, the controller starts looking for signals
from the slip sensor. As the force is gradually decreased,
individual nibs start to pop loose and vibrate[2]. These vi-
brations propagate through the skin and cause the output
of the slip sensor to go above a certain threshold which is
set according to the amount of ambient noise. The grasp
force is then reset to the initial value and the exponential
decay recommences.

Plot 2 of Figure 4 shows the RMS output of the slip
sensor. It should be noted that the jumps in the curve
are a combination of incipient slip signals superimposed
on acceleration signals that appear as the system starts to
respond to the slip event by increasing the normal force.
These additional acceleration signals take some time to
subside, therefore the system must be programmed to take
this into account so that it does not continue to increase
the normal force unnecessarily.

As the experiment progresses, further slips are de-
tected and the normal force is again increased. As the
plots in Figure 4 indicate, over a period of ten seconds
the process is fairly repeatable. Referring to the object
position plot in Figure 4, it can be seen that once the
slip sensor is activated, the object moves very little (ap-
proximately 0.25mm) throughout the 8 second trial. As
a further indication of negligible gross sliding, there is no
significant activity in the fourth plot, showing the output
from the accelerometer attached to the object.

Essentially similar results were obtained with a vari-
ety of other materials including smooth paper, fine cloth
and teflon. Object drift was minimal, ranging from 0.25
to 0.40mm for all materials. As expected, the results were
best for rough materials such as sandpaper, which elicited
the strongest incipient slip signals. The performance while
gripping teflon is better than was initially expected, con-
sidering the lack of texture on the teflon samples and the
comparatively small difference between the dynamic and
static coefficients of friction for teflon. Evidently, a sharp
discrete "plucking" of the nibs on the sensor skin surface
is not necessary. Rougher materials also allowed the nor-
mal force to decay to lower values before slip occurred

(consistent with their higher coefficient of friction) and
therefore produced longer periods of decay between trig-
gering events and thus fewer triggers over the duration
of the experiment. Coefficients of friction for the various
materials against the skin ranged from 0.50 to 0.70.

To further investigate the performance of the system,
experiments were run with objects having dirty and wet
surfaces. No significant changes in performance were ob-
served except for small increases in object drift. Problems
were encountered however when the surfaces were coated
with oil or soap. In those instances, the sensor clearly was
not able to detect any incipient slip signals and significant
slip occurred. This is most likely due to the fact that the
oil and soap effectively damped out the vibrations of the
nibs at the periphery thus inhibiting the sensor's perfor-
mance. Note that humans also have difficulty maintaining
an appropriate grasp force with such materials.

The experiments indicate that grasp force control based
on incipient slip sensing is quite feasible in a laboratory
environment with a variety of object materials. How-
ever, practical implementation of such an approach re-
quires that the system also not be unduly influenced by
mechanical noise (e.g., structural vibrations) and electro-
magnetic noise. We have found a couple of ways to address
this problem. The first is to use fingertips for which a thin,
textured skin covers a soft foam core. The foam helps to
isolate the skin acceleration sensor from vibrations in the
manipulator so that the skin sensor is predominantly af-
fected by vibrations occurring within the contact area.
As a comparison of the skin acceleration and object accel-
eration plots reveals, localized contact vibrations can be
measured relatively independently of vibrations within the
grasped object. In addition, an analysis of the unfiltered
signals from the skin acceleration sensor reveals that for
the combinations of skin and foam core tested, the vibra-
tions of interest are in range of 400-700Hz for all materials
tested. This is not surprising if we consider that the vi-
brations resulting from localized slips occur at frequencies
determined primarily by the geometry and material of the
skin itself. Figure 5 shows a detail of a raw skin accel-
eration signal (before RMS-DC conversion), during which
the incipient slip signal can be seen during the first 10
milliseconds, at a frequency of approximately 600Hz. As
a result, bandpass filtering is useful for reducing the sensi-
tivity of the system to mechanical vibrations produced by
the manipulator, which occur at considerably lower fre-
quencies.

More work remains to be done on determining the in-
fluence of the shape of the finger on the behavior of the
nibs at the edge of the contact patch. However, it is prob-
ably safe to assume that the local radius of curvature at
the periphery of the contact patch determines how rapidly
the nibs become unloaded. Note that for a large deforma-
tion of the skin and core, the local radius becomes quite
small and remains relatively constant for small changes in
the normal force, which was the case for our experiments.
This small radius is desirable since it means that the nibs
will "pop" free instead of being gradually released thus
providing vibrations that are easier to detect.

Also, it should be mentioned that breakaway nibs at
the edges of the contact area do not necessarily preface
slip; they can also occur as the finger is loaded/unloaded
and the contact patch changes. However, when an object
is about to slip, breakaway nibs at the edges will certainly
occur since the pressure at the edges will tend towards

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[2]If the accelerometer is connected to an audio amplifier and loudspeaker,
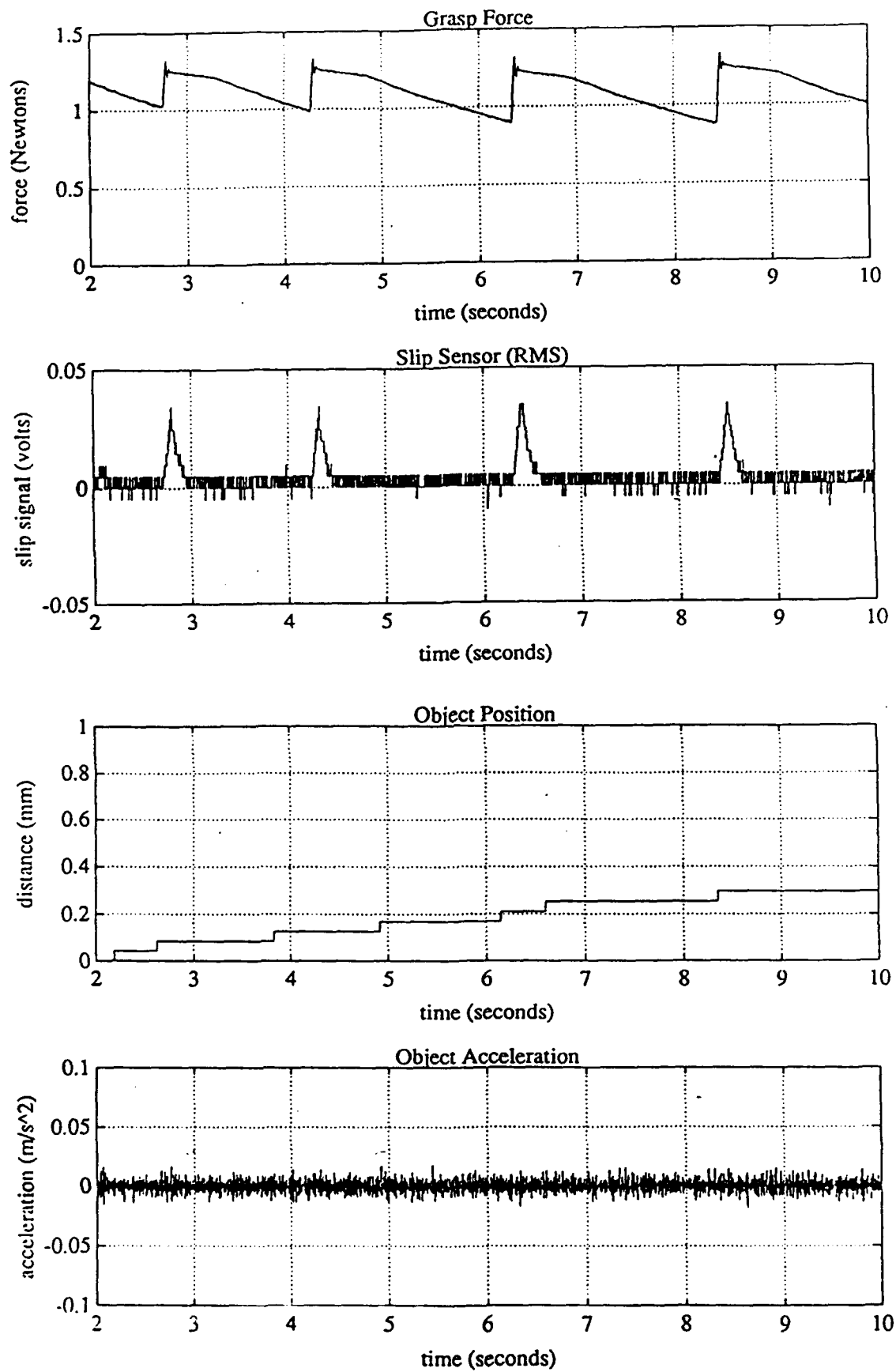these discrete "pops" can be heard clearly above the ambient noise.

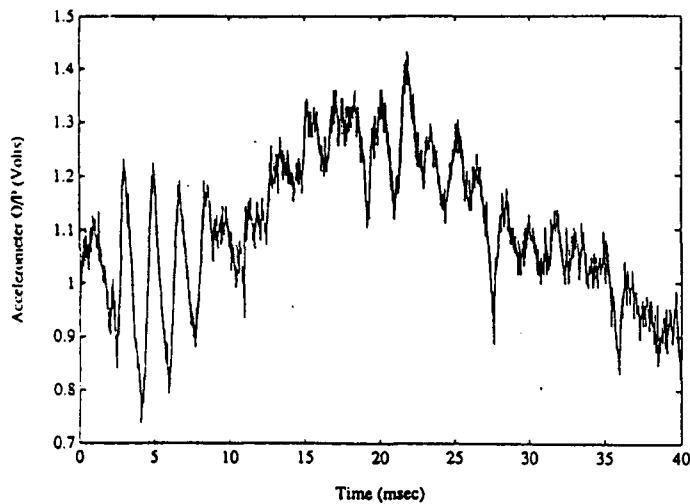Figure 4: Experimental results for fine grain sandpaper

Figure 5: Unprocessed slip acceleration signal during a local slip

zero while the shear traction will not [Schallamach57].

5 Conclusion and future work

A grasp force control strategy was implemented, patterned after the responses reported in the physiology literature for human subjects [Westling and Johansson 84, 90]. The experimental results indicate that successful grasp force control can be achieved, based on the sensing of incipient slips between an instrumented robotic fingertip and an object. The signals are produced by vibrations that occur in the skin of the robotic fingertip as individual protrusions on skin surface start to lose their grip. The first protrusions to slip are typically those located near the periphery of the contact area, where the contact pressure is smallest. These incipient slip signals precede gross sliding of the ob-'ect and provide enough time to increase the normal force at the contact to prevent gross sliding from occurring. The experimental results were not greatly affected by variations in the material properties of the grasped object and also indicate that the force controi strategy is adequately immune to mechanical vibrations in the manipulator.

A number of extensions immediately suggest themselves. The first is of course to apply the grasp force control strategy in manipulation tasks with multiple fingers. Work remains to be done on optimizing the grasp force decay rates and ramp-up strategies to make the system more robust with respect to disturbances. Also, a better understanding of the contact mechanics involved will lead to an improved finger design, better suited to incipient slip detection. The methods used for the experiments described in this paper were inspired by human models. However, as a robotic manipulator can respond considerably faster than the approximately 80msec latency associated with human grasp force updating, it should be possible for the robot to maintain more precise force control than a human. Indeed, even with the present control, the manipulator is in some ways better able to maintain control than a human subject. For example, if one tugs hard enough on the object to initiate some gross slip, the robot responds fast enough to avoid loosing control of the object. By contrast, humans often have difficulty responding fast enough to large, unexpected changes in object loading to recover control of a grasp.

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